A Flight Experiment to Determine GPS Photochemical Contamination Accumulation Rates

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ABSTRACT

It has recently been suggested that photochemically deposited contamination, originating from volatiles outgassed by the spacecraft itself, may be responsible for the anomalous degradation in power seen on the GPS Block 1 vehicles. In an attempt to confirm, or deny, the photochemical deposition rates predicted, a study was undertaken to design a flight experiment to be incorporated on the GPS vehicles currently in production. The objective of this study was to develop an inexpensive, light-weight instrument package that would give information on the contamination levels within a few months of launch. Three types of apparatus were investigated, Quartz Crystal Microbalances (QCM's), modified solar cells, and calorimeters. A calorimeter was selected due primarily to its the impact on the production schedule of the GPS vehicles. An analysis of the sensitivity of the final design will be compared to the predicted contamination accumulation rates in order to determine how long after launch it will take the experiment to show the effects of photochemical contamination.

SYMBOLS

Q''_L - heat loss due to thermal coupling

$R(\lambda)$ - spectral reflectance

S - incident heat flux (W/m^2)

T - temperature (K)

x - thickness of contaminants (m)

α_s - solar absorptance of a clean material

$\alpha_s(x)$ - solar absorptance of a contaminated material

$\alpha(\lambda)$ - spectral absorptance (of an optical solar reflector)

$\alpha_c(\lambda)$ - spectral absorptance of contaminant layer

ε - emissivity

$\Phi(\lambda)$ - solar flux

σ - Boltzmann's constant

λ - wavelength (m)

INTRODUCTION

An analysis of the molecular outgassing rates from the GPS vehicles, Figure 1, determined that there was a sufficient amount of matter being emitted by the spacecraft that if a small fraction of matter which impinged upon the solar panels were to stick this could account for the degradation in power production observed on the GPS Block I vehicles, Tribble and Haffner, [1]. It was proposed by Stewart et. al, [2], that a photochemical reaction initiated by the solar UV could be the mechanism responsible for fixing the contamination onto the solar panels as similar phenomena are known to occur in the laboratory, [3-5]. Subsequent to the investigation of the GPS Block I contamination similar calculations were performed for the GPS Block II vehicles currently being launched and it was found that there should be a noticeable degradation in power, attributed to photochemical contamination, on GPS Block II vehicles 13 - 21. GPS Block II vehicles 22 - 40 should be relatively immune to this contamination as EMI seals employed on these vehicles have effectively eliminated the outgassing paths from the vehicle to the solar panels. The objective of this study is to develop a design for a flight experiment, which could be included on one of the early GPS Block II vehicles, that could confirm, or deny, the accuracy of the predicted photochemical contamination accumulation rates.

The most obvious location for an experiment designed to measure the degradation of the solar panel output is on the solar panels themselves. Tribble and Haffner, [1], were able to predict the impact rate and accumulation rate of contaminants for various locations on the GPS Block II solar panels. Consequently, by placing a monitor in an area where high accumulation is expected and comparing it with a monitor in an area where little accumulation is expected any difference in readings should be attributable to contamination as the radiation environments for each monitor would be identical. A major concern in the development of a flight experiment is that any recommended design be able to be implemented on a production vehicle with a minimum of integration problems and/or scheduling delays. As was previously mentioned vehicles 22 - 40 have EMI closeouts which reduce the outgassing onto the arrays, consequently vehicles 13 - 21 are the best candidates for a contamination experiment, with GPS 15 currently offering the most lead time. A major constraint is that a workable design must be one that can be agreed upon, procured, and implemented into the acceptance test flow without delaying the processing of the vehicle. (As a check upon the effectiveness of the EMI seals on vehicles 22 - 40 the contamination experiment could also be flown on a later vehicle, but these launches are far enough into the future that time is not yet a significant factor.)

The sections that follow discuss some of the possible experimental methods that could be used to obtain data on the contamination levels and the problems involved in integrating these experiments into a production vehicle. It will be shown that a calorimeter, utilizing optical solar reflector's (OSR's) backed with thermistors, could be developed in time for inclusion on GPS 15. This experiment would have the advantage of requiring minimal qualification testing as it is essentially identical to one previously flown on GPS 5 and 6.

SPACECRAFT INTEGRATION REQUIREMENTS

GPS 15 is tentatively scheduled for launch in February of 1991. As the spacecraft systems are all intact maintaining this launch schedule implies that there can be no significant rewiring or telemetry changes. Since the most favorable location for the experiment is on the solar panels themselves the experiment must be light-weight and small enough that it not interfere with the stowing or deployment of the panels, or affect the balance of the vehicle. There is

also the problem of bringing the data from the solar panels to the body of the spacecraft.

All of the electronic leads to/from the solar panels are via slip rings on the solar array booms. Bypassing the slip rings and hardwiring an experiment directly into the body of the vehicle could conceivably cause interference with the deployment or normal operations of the panel. Also, during eclipse conditions the wiring could become so stiff that the torque supplied by the solar array drive would be unable to rotate the panels. Obviously, this is unacceptable, so the experiment is confined to the use of the slip rings.

GPS 15 currently has two spare slip rings per boom. The remainder of the slip rings are used for power or data transmission into the spacecraft. There are a number of thermistors located on the GPS solar panels which are used to record the temperature of the panels during orbital insertion or to verify the deployment of the panels,. Data from the first 5 GPS Block II launches indicate that there is no problem with overheating of the panels during orbital insertion. Consequently, slip rings currently allocated to one thermistor (per boom) could be reallocated to a flight experiment leaving at most four available slip rings per boom.

REVIEW OF AVAILABLE EQUIPMENT

A review of the experimental equipment that is currently available on the market for use in determining contamination levels revealed three possible alternatives: Quartz Crystal Microbalance's (QCM's), modified solar cells, and calorimeters. Each of these alternatives is discussed individually in the subsections that follow, with particular attention being paid to the data that each experiment would yield and its ease of integration into the current spacecraft.

Quartz Crystal Microbalances

A QCM consists of 2 piezoelectric crystals which resonate at known frequencies. One crystal is exposed to the environment and as mass accumulates on its surface its resonant frequency is lowered in a predictable manner. By comparing the beat frequency between an exposed crystal and a shielded crystal one is able to determine the accumulated mass/unit area. The temperatures of the crystals, which are identical, may be controlled externally or allowed to float with the environment in order to eliminate, or measure, the effect of temperature on mass accumulation.

As QCM's are able to measure mass accumulation directly they have seen extensive use on spacecraft contamination monitoring programs, Wallace, [6,7], Hall, [8]. Unfortunately, QCM's require more supporting electronics than can be accomodated by the 4 available slip rings.* Consequently, QCM's were dropped from consideration as they did not meet the criteria for easy, quick integration into the spacecraft.

It should be noted that even though QCM's will directly measure the amount of mass collected, they yield no information about the transparency of the material. Since a very thin layer of a highly absorptive material may have the same effect on a solar cell as a thick layer of a more transparent material QCM's would not yield a complete analysis of the solar panel contamination.

Modified Solar Cells

As it was the degradation of power of the GPS Block I solar panels that was

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*QCM Research, Laguna Beach, CA.

the first indication of a possible outgassing problem it would seem logical to devise an experiment that would measure the effects of contamination on solar cells directly. A typical solar cell is constructed by combining about 0.2 microns of an n-type silicon, (i.e., a type of silicon where there is an abundance of electrons in the conduction band, which can be obtained by doping silicon with phosphorous), with about 200 microns of a p-type silicon, (a type of silicon having a depletion of conduction electrons, which can be obtained by doping silicon with boron), Tada et. al, [9]. As a result of the different properties of the two silicons, electrons from the n layer will diffuse into the p layer and an electric field will be produced, typically within 1 - 5 microns of the junction. As photons enter the n layer they will undergo collisions with atomic electrons and, as a result, boost more electrons into the conduction band. Blue light of wavelength 0.35 microns is 99% absorbed within 0.2 microns of the surface, whereas red light of wavelength 0.94 microns travels 200 microns before being 99% absorbed. As the electrons are liberated within the silicon the electric field in the vicinity of the junction will accelerate electrons toward the front surface. By placing electrical contacts on the front and rear surface of the n-p cells the electrons can be drawn off as a current and used as a power source. (The voltage at which the current is supplied is related to the strength of the electric field at the n-p junction.)

Obviously solar cells, like everything else, will not be 100% efficient at converting the light to electrical power. When an electron undergoes a collision with a photon and receives enough energy to escape the pull of the atomic nucleus, the atom will be left with a net positive charge. As the liberated electron moves through the cell it will only be a matter of time before it passes too close to an atom which is missing an electron and is recaptured. The time that an electron is typically able to move through the cell is called the lifetime, τ (s), which is defined as the time before 1/e of the electrons are recaptured. During their lifetime the electrons are able to travel a distance called the diffusion length, L (m), where L = $\sqrt{D\tau}$, D (m^2/s) being the characteristic diffusion coefficient for the silicon material. Typically, diffusion lengths are on the order of 200 microns. Consequently, an n-p solar cell is much more efficient at converting blue light to electricity than red light, as the electrons produced by the red light must travel a distance on the order of the diffusion length, and are much more likely to recombine with an atom, before reaching the junction.

Similarly, it is seen that radiation, which decreases the diffusion length by creating atomic displacements, site defects, etc., would chiefly reduce the cells ability to convert red light to electricity by further limiting the fraction of 'red' electrons that are able to reach the junction, this is illustrated in Figure 2. Conversely, contamination mainly affects a cells ability to convert blue light to electricity, see Figure 3, by absorbing the blue light before it reaches the cell. Consequently, it would be straightforward to develop two groups of 'modified solar cells' to help determine the effects of contamination on the GPS solar panels. One group of such cells would be designed to be sensitive to blue light, by being thinner than usual so as to allow fewer red light photons to liberate electrons. The second group of cells would be designed to be sensitive to red light, by placing the p-type silicon towards the sun as opposed to the n-type, i.e. a p-n type solar cell. Since the majority of the conduction electrons produced by blue light originate within 0.2 microns of the surface the 'blue' electrons would then have a harder time reaching the junction, 200 microns away. By flying groups of the special cells on the GPS solar panels a reduction in power of the 'blue sensitive' cells would indicate a degradation due to contamination, while a loss of power from the 'red sensitive' cells would indicate radiation damage.

The advantage of this type of experiment is that the special cells could be used to supply extra power for the vehicle. Unfortunately, for the disadvantages outweight the advantages. Due to the slow buildup of contaminants predicted on

the GPS solar panels it appears as though it would take more than one year for the 'blue sensitive' cells to show the effects of contamination once on-orbit, much longer than is desired. Also, more than one year would be required to manufacture and test the special cells.* In addition, the special cells would require significant rewiring and telemetry changes to the spacecraft which again implies that it would be impossible to implement on GPS 15. Consequently, this concept was not pursued further.

Calorimeters

A material that is in thermal equilibrium with its surroundings will absorb and re-radiate heat according to the relation

$$\alpha S = \varepsilon \sigma T^4. \tag{1}$$

For materials carried into space, the incident heat flux will be supplied by the sun and the absorptance is given by

$$\alpha_s = \int \alpha_s(\lambda)\Phi(\lambda)d\lambda / \int \Phi(\lambda)d\lambda \tag{2}$$

If a clean material becomes contaminated with a thin layer of contaminants its absorptance is changed according to the relation

$$\alpha_s(x) = \frac{\int [1-R(\lambda)exp^{-2\alpha_c(\lambda)x}]\Phi(\lambda)d\lambda}{\int \Phi(\lambda)d\lambda}, \tag{3}$$

$\alpha_c(\lambda)$ has been measured experimentally for typical spacecraft contaminants, Hall, [10], and references therein, therefore knowing $R(\lambda)$ will allow us to compute $\alpha_s(x)$.

The change in absorptivity is related to the measured temperature change by the relation

$$\Delta\alpha_s = \frac{4\varepsilon\sigma T^3}{S}\Delta T + \frac{\sigma T^4}{S}\frac{\partial\varepsilon}{\partial T}\Delta T \tag{4}$$

For high emissivity materials, such as fused silica, the emissivity will be insensitive to both temperature changes and the presence of a thin contaminant layer. Consequently, the last term may be neglected. Therefore, we see that a change in temperature of a sample, can be related directly to the thickness of contaminants,

$$\Delta T = \frac{S}{4\varepsilon\sigma T^3}[\alpha_s(x) - \alpha_s] \tag{5}$$

Experimental apparatus based on this techinque are referred to as calorimeters. A number of them have been flown as one method of determining contamination levels, Hall and Fote, [11], and Hall, [8]. Of particular interest however, is the calorimeter experiment flown on GPS vehicles 5 and 6, Pence and Grant, [12]. These instruments consisted of thermal control coatings over an aluminum substrate which was thermally isolated from the rest of the vehicle, see Figure 4. A thermistor on the underside of the aluminum substrate was used to infer the temperature of the thermal control coatings.

*Spectrolab, Sylmar, CA.

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A simplistic design such as this, if properly calibrated, is capable of yielding information on the thickness of contaminants on the GPS solar panels. This design has the advantage of being previously space-qualified and flown, relatively quick and inexpensive to procure and assemble, and requires only 2 electrical leads per calorimeter. Consequently, this design was selected as the leading candidate.

RECOMMENDED DESIGN AND CALIBRATION TECHNIQUES

The calorimeters flown on GPS vehicles 5 and 6 are small, the inner sample itself measures 2.06" square and the outer holder measures 3.4" square, light-weight, 0.45 lbs each, and require only two electrical leads per calorimeter. It should be possible to include four of them, two per boom, on GPS 15. However, since time is a major constraint it would be quicker to install only one calorimeter per boom. In order to obtain the maximum amount of information in the smallest time the calorimeters could be placed on the solar array boom, one inboard and one outboard. This configuration would not offer redundancy in the case of failure of one of the calorimeters but would have the advantage of requiring no wiring changes. The redundant thermistors would simply be disconnected and the calorimeters would then be spliced into the existing wiring in a minimal amount of time. The resulting data should indicate changes in the temperatures, and thus the absorptances, of the inboard calorimeter within a few months. Since the outboard calorimeter would be subjected to an identical radiation environment, ignoring any shielding effects from the GPS vehicle itself, which are expected to be minimal, any differences in the absorptance of the inboard and outboard samples will be due entirely to contamination. GPS structures personnel have analyzed the effect of placing these calorimeters on the solar panel booms and have found it to be within tolerances. Consequently, once the authority to proceed has been given, the fabrication and testing of the calorimeter could be accomplished in parallel to the acceptance test flow for GPS 15. A brief discussion of the calibration of the calorimeters is warranted in order to understand the sensitivities of the experiment and the exact timescale that would be needed to obtain meaningful data on the contamination deposition rates.

As discussed by Brosmer et. al, [13], in all realistic applications there will be a heat leak, from the boundary to the thermally isolated substrate, affecting the thermal performance of the calorimeter. Consequently, the change in absorptance is more appropriately given by

$$\alpha_s = (\epsilon\sigma T^4 + Q^{''}_L)/S \qquad (6)$$

where $Q^{''}_L$ is the heat loss due to thermal coupling. The relative uncertainty of the absorptance is given by

$$\frac{\Delta\alpha_s}{\alpha_s} = \frac{(\Delta\epsilon/\epsilon) + (4\Delta T/T)}{1 + Q^{''}_L/\epsilon\sigma T^4} + \frac{\Delta Q^{''}_L/Q^{''}_L}{1 + \epsilon\sigma T^4/Q^{''}_L} - \frac{\Delta S}{S} \qquad (7)$$

Thus, the uncertainty in α_s depends on the uncertainty associated with measurements of $\epsilon, T, S,$ and $Q^{''}_L$.

As was previously mentioned, the change in emissivity of fused silica, due to a thin contaminant layer or temperature changes, is negligible. Brosmer et. al list the maximum uncertainty at 1.3%. The incident solar flux, S, can be measured to within 0.2%, Willson, [14], with daily fluctuations rarely exceeding 0.1%. The uncertainty in temperature is dependent upon the noise level associated with the slip rings and the calibration of the thermistor. This uncertainty is estimated at about 5.0% over a 170° C temperature range.* This can be greatly improved upon,

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to about 1.0% or less, by confining the measurements of temperature to a smaller range. This will be the case with the calorimeters as variations in T during periods of solar illumination should be small. The final source of error is associated with the measurement of the heat loss term, Q''_L. The absolute value of Q''_L will have to be estimated during calibration tests, Brosmer et. al, [13], and is typically the largest source of error, being perhaps as large as 5.0%.

A few words are in order, concerning the values of α_s that we expect to measure on GPS 15. The inboard and outboard calorimeters are predicted to accumulate contaminant levels of 144 Å and 72 Å, respectively, at the end of 30 days. This would increase the value of α_s from 0.060, for a clean surface, to about 0.068, (0.064), for the inboard, (outboard), calorimeter. (A more realistic value for the beginning of life absorptance would probably be 0.080, which would result in end of life values of about 0.090 and 0.085, respectively, for the inboard and outboard calorimeters.) As this increase, (13.3% and 6.6%, respectively), is well within the accuracy we predict for our calorimeter, we would expect to see measureable changes in α_s within 30 days of arriving on orbit. This has been confirmed by the operation of the calorimeters on GPS 5 and 6.
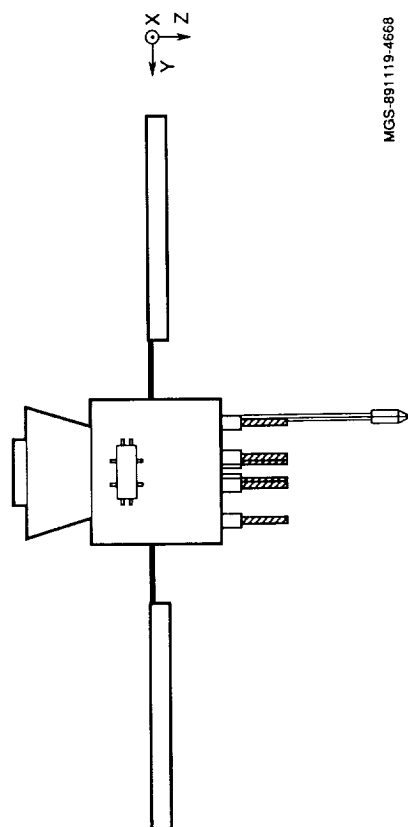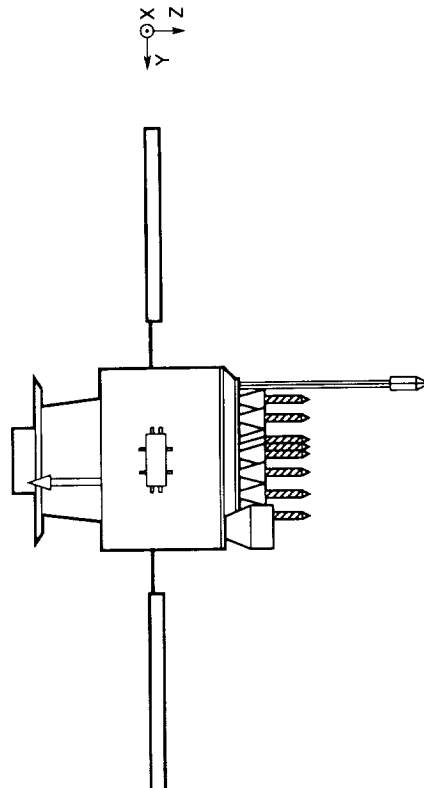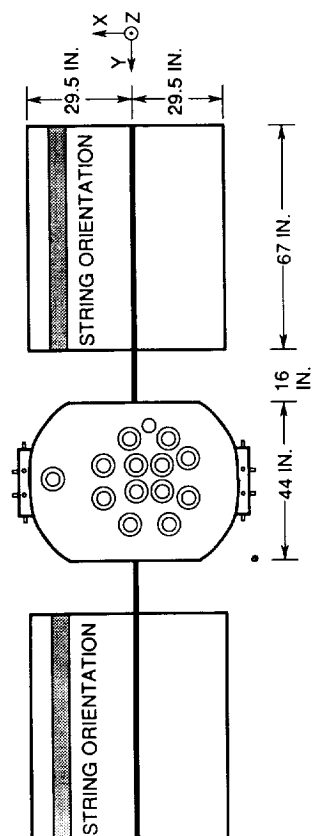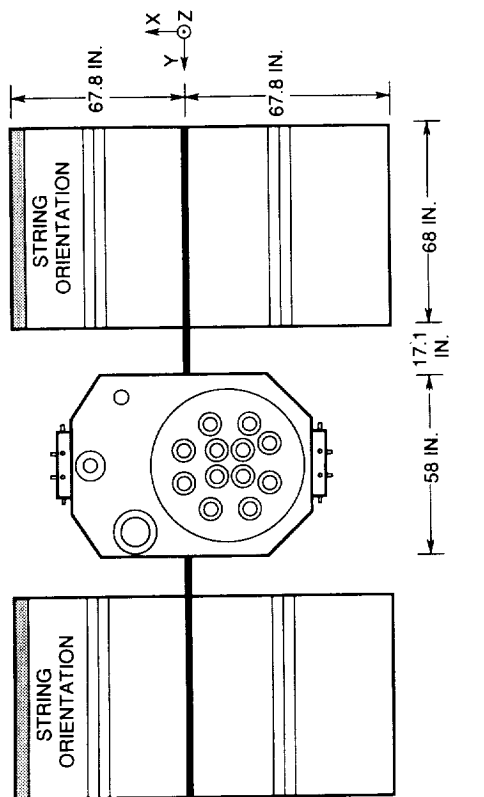
SUMMARY AND CONCLUSIONS

This report has examined a number of potential experiments that could be included on the GPS 15 vehicle in an attempt to directly measure the on-orbit accumulation of contaminants. It was determined that an experiment consisting of 2 calorimeters, based on the GPS Block I design, could yield the desired information and, at the same time, minimize the impact to the vehicles acceptance test flow schedule. The experiment should indicate the effects of the contamination within a few months of launch and would be an important in situ test of a topic that is currently the focus of intensive research efforts throughout the aerospace industry.

Unfortunately, as of 1 June 1990, authority to proceed with the installation of calorimeters on GPS vehicles 15 was still pending. Not enough time remains before the launch of GPS 15 to complete installation of a calorimeter on this vehicle. It may still be possible to proceed with a calorimeter experiment on a later GPS vehicle, however this decision has yet to be made.

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STRING ORIENTATION

STRING ORIENTATION

67.8 IN.

67.8 IN.

68 IN.

17.1 IN.

58 IN.

X
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BLOCK II

STRING ORIENTATION

STRING ORIENTATION

29.5 IN.

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67 IN.

16 IN.

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BLOCK I

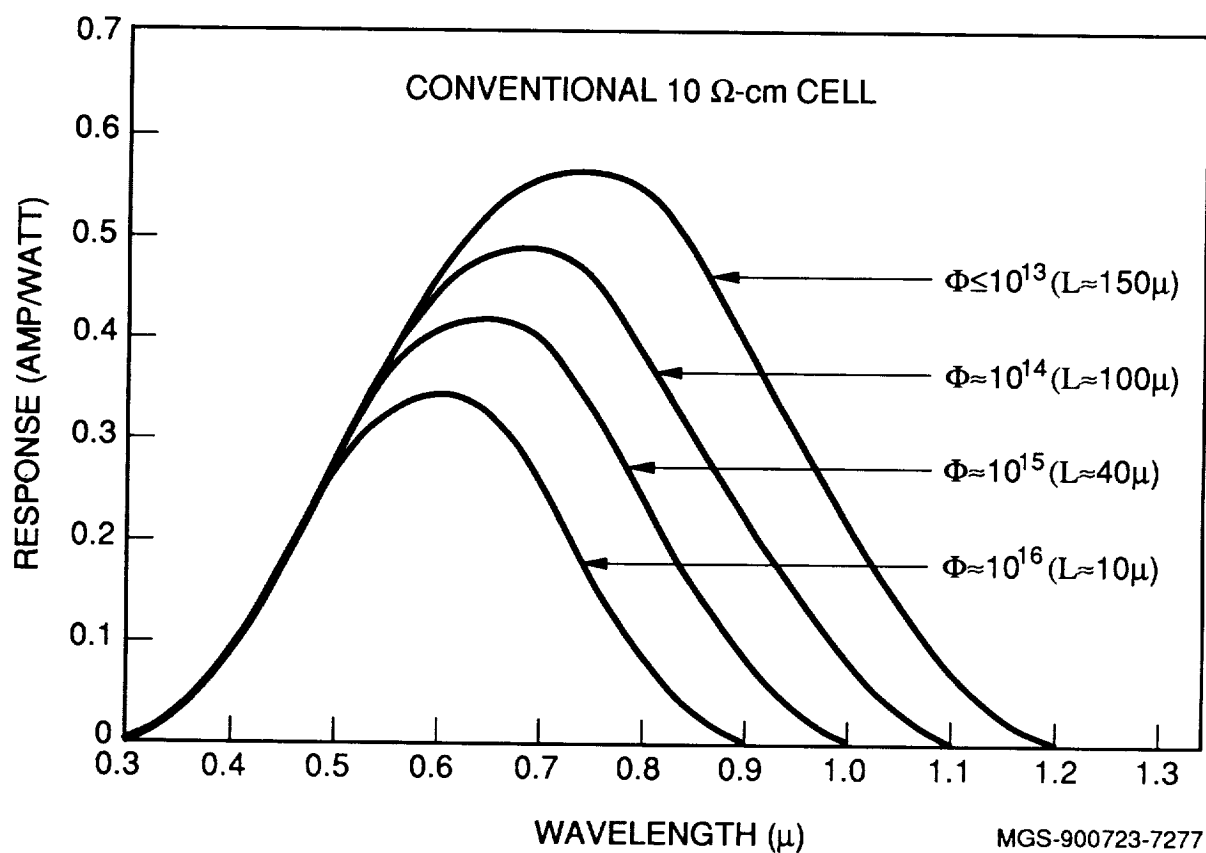Figure 1. The GPS Block I and Block II Vehicles.

Figure 2. The Response of a Typical Solar Cell Subjected to Increased Radiation Fluences. (The units on Φ are equivalent 1 MeV electrons.)
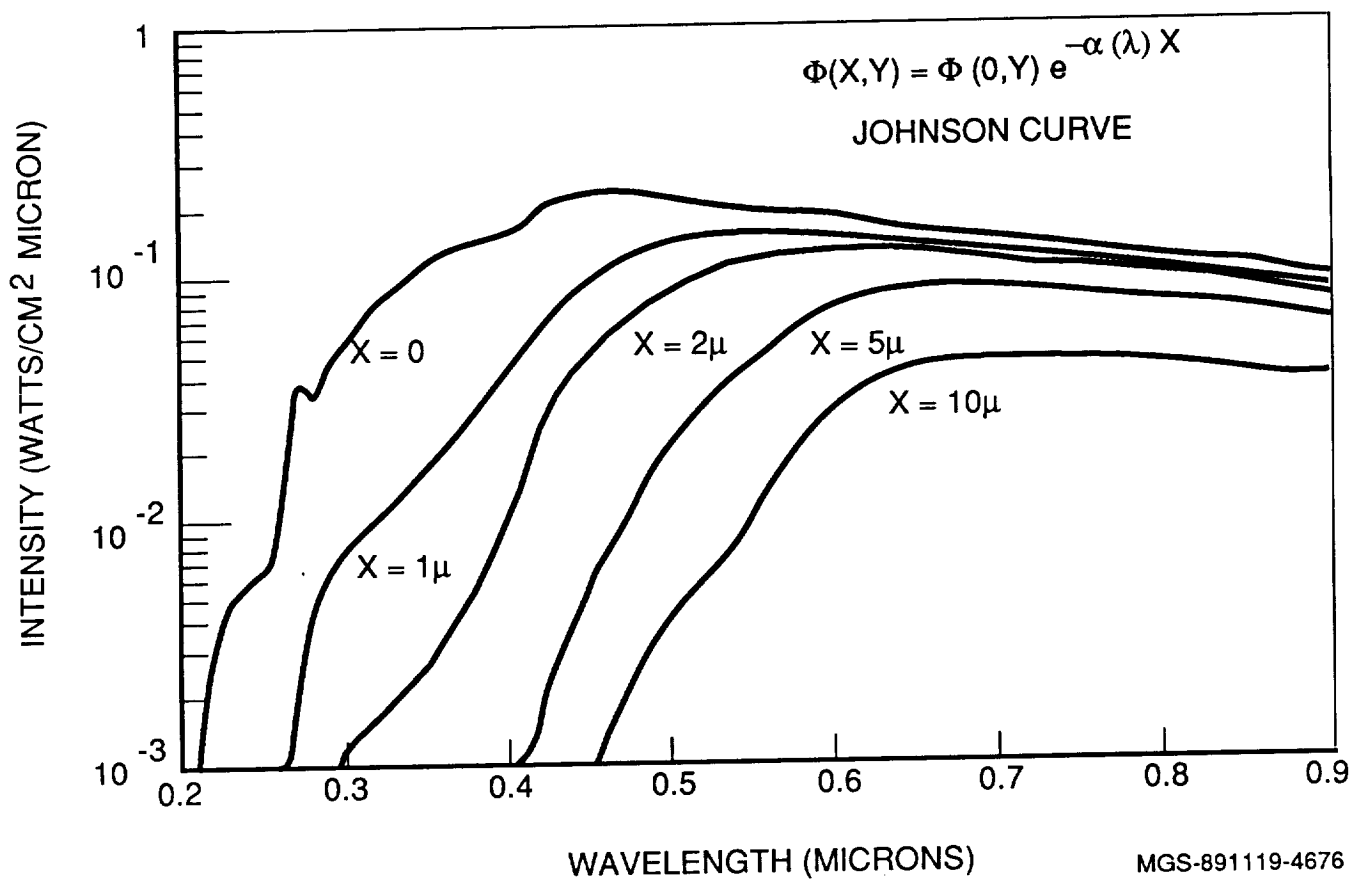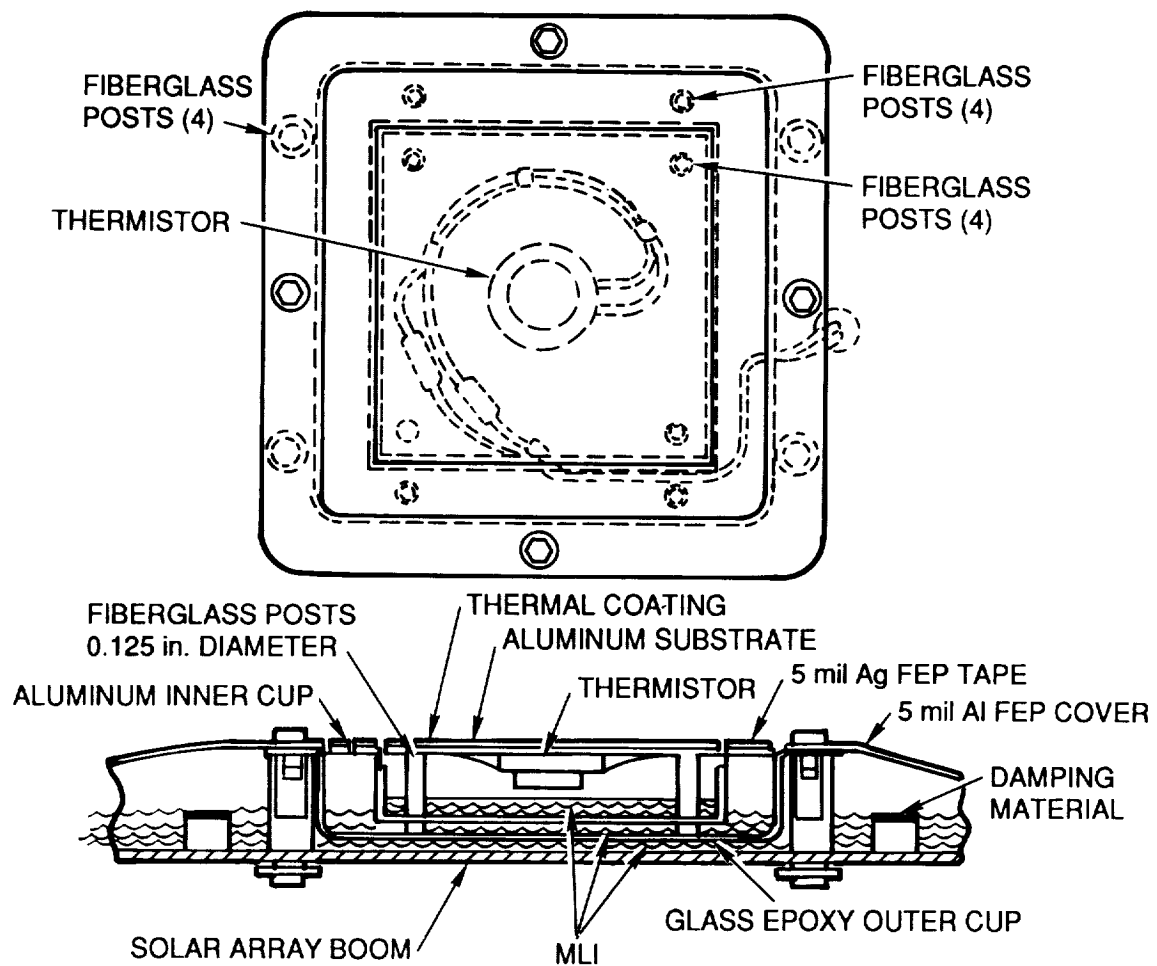
Figure 3. The Effect of Contamination Upon Light Transmission.

FIBERGLASS POSTS (4)

FIBERGLASS POSTS (4)

THERMISTOR

FIBERGLASS POSTS (4)

FIBERGLASS POSTS 0.125 in. DIAMETER

THERMAL COATING

ALUMINUM SUBSTRATE

ALUMINUM INNER CUP

THERMISTOR

5 mil Ag FEP TAPE

5 mil Al FEP COVER

DAMPING MATERIAL

SOLAR ARRAY BOOM

MLI

GLASS EPOXY OUTER CUP

MGS-900725-7278

Figure 4. The Proposed Calorimeter Design.

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